Training Sequence Aided MC-CDMA Scheme with High Spectrum Efficiency

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SUMMARY This letter presents a novel multi-carrier code division multiple access (MC-CDMA) system called time domain synchronous MC-CDMA (TDS-MC-CDMA). Aided by the new training sequence (TS) with perfect autocorrelation in the time domain and flat frequency response in the frequency domain, the proposed TDS-MC-CDMA system outperform the traditional MC-CDMA system in terms of spectrum efficiency by about 10%. Simulations are carried out to demonstrate the good performance of the proposed scheme.

key words: MC-CDMA, TDS-MC-CDMA, spectrum efficiency, training sequence

1. Introduction

The challenge of transmitting high-speed (close to 1 Gb/s) data with high quality under a severe frequency-selective fading environment makes MC-CDMA technology a promising candidate for the next generation broadband wireless communication systems [1]. In essence, MC-CDMA is a multi-carrier communication system, and the cyclic prefix (CP) in typical orthogonal frequency division multiplexing (OFDM) systems is also adopted as the guard interval (GI) in MC-CDMA systems to combat inter-symbol-interference (ISI). However, the CP will lower the spectrum efficiency of the MC-CDMA systems. In addition, pilots occupying about 10% of the total subcarriers are required for synchronization and channel estimation (CE) in MC-CDMA systems [2], the spectrum efficiency is further lowered. In this letter, a novel MC-CDMA system called time domain synchronous MC-CDMA (TDS-MC-CDMA) with higher spectrum efficiency than the conventional MC-CDMA systems is proposed.

2. TDS-MC-CDMA System Architecture

In this section, a novel frame structure for the MC-CDMA signal is proposed. Based on the new frame structure, the system architecture of the training sequence aided TDS-MC-CDMA scheme is then presented.

2.1 Frame Structure

Figure 1(a) shows the frame structure of a conventional MC-CDMA system, where the last portion of the multi-carrier signal is copied and put to the front of the signal to combat ISI. For coherent modulation, pilots in the frequency domain are required to facilitate synchronization and CE at the receiver, which further reduces the capacity. The proposed frame structure for the novel TDS-MC-CDMA system is presented in Fig. 1(b), where the known training sequence (TS) is proposed as the GI of the multi-carrier signal. Since the TS is known at the receiver and can thus be estimated and removed, Deneire has proven that the concept of TS is equivalent to CP in single-carrier transmission [3]. In addition, the known TS is used for synchronization [4] and iterative padding subtraction (IPS) is adopted to remove the ISI from the TS to the following multi-carrier data block [5]. Therefore, no extra pilots are needed, leading to the increase of bandwidth efficiency by about 10% for the proposed system. One example of the TS is the pseudo-noise (PN) sequence that has been successfully used in the time domain synchronous OFDM (TDS-OFDM) system, which is the key technology of Chinese national digital television terrestrial broadcasting (DTTB) standard [6].

Unlike the TDS-OFDM system where PN sequence is used as TS, we proposed a new TS called PN-MC (multi-carrier PN sequence) for the TDS-MC-CDMA system. The PN-MC sequence \( p = \{p(n)\}_{n=0}^{N_p-1} \) in the time-domain is generated by

\[
p(n) = \frac{1}{\sqrt{N_p}} \sum_{k=0}^{N_p-1} P(k) \exp \left( j \frac{2\pi n k}{N_p} \right),
\]

where \( P = \{P(k)\}_{k=0}^{N_p-1} \) is the frequency-domain binary sequence whose \( N_p \) elements are randomly selected from \{1, -1\}, i.e., \( P(k) \in \{1, -1\} \). Compared with traditional PN sequence used in TDS-OFDM, the proposed PN-MC sequence has the following advantages:

1) Arbitrary length: Unlike the m-sequence whose length is confined to be \( 2^n - 1 \), where \( n \) is an integer, the length of the PN-MC sequence could be any integer larger than zero. Therefore, PN-MC is more suitable to be used as GI whose length can be freely configured according to the system requirements.

2) Best CE performance: According to [7], minimum
CE error could be achieved if the TS has constant envelope in the frequency domain, i.e.,
\[ |P(0)| = |P(1)| = \cdots = |P(N_p - 1)|. \] (2)

Obviously, the proposed PN-MC sequence meets this requirement, while the PN sequence does not. Figure 2(a) and Fig. 2(b) compare the frequency response of the extended PN sequence (PN420 mode in [6] is assumed) in TDS-OFDM and the proposed PN-MC sequence in TDS-MC-CDMA. Therefore, better CE performance will be achieved for the proposed TDS-MC-CDMA system. In addition, unlike the Chu sequence with complex values, the binary values \{1, -1\} of the PN-MC sequence in the frequency domain will simply the least square (LS) channel estimation method.

3) **Ideal autocorrelation function**: Due to the facts that the autocorrelation function of one specific sequence equals to the cyclic convolution of the sequence itself, and the time-domain cyclic convolution is equivalent to the multiplication of the frequency responses in the frequency domain, so the frequency response of the autocorrelation function of the proposed PN-MC sequence also has constant envelope. This indicates that the PN-MC sequence has ideal autocorrelation function, i.e.,
\[ \sum_{k=0}^{N_p-1} p(k)p^*(k + \tau) \mod (N_p) = \begin{cases} N_p & \tau = 0 \\ 0 & \tau \neq 0 \end{cases}, \] (3)

where \((\cdot)^*\) is the complex conjugation, \(\mod(N_p)\) means \(N_p\)-point modulus. However, the autocorrelation of the PN sequence is good but not ideal. Ideal autocorrelation is preferred for both timing synchronization and channel estimation. For example, as for the channel impulse response (CIR) denoted as \(h(n) = \delta(n - 80) + \delta(n - 220)\), Fig. 2(c) and Fig. 2(d) compare the correlation peaks of the 255-point PN sequence and PN-MC sequence for channel estimation, under the signal-to-noise ratio (SNR) of 5 dB. It is clear that PN-MC is superior to PN sequence.

In addition, as the TS as well as GI, PN-MC is used for every signal frame, so rapid channel state information (CSI) updating speed is guaranteed, leading to the good performance over fast time-varying channels.

2.2 System Architecture

Based on the frame structure shown in Fig. 1(b), the system architecture of the proposed TDS-MC-CDMA system is shown in Fig. 3. The user specific data after spreading by the corresponding code are combined together before serial-to-parallel (S/P) conversion and constellation mapping. Inverse discrete Fourier transform (IDFT) is then applied to the data block \(X\) in the frequency domain with the length of \(N\) to generate the multi-carrier signal \(x\) in the time domain. Note that no pilots are inserted in the frequency domain, which are required in the traditional MC-CDMA systems. After that, the known training sequence PN-MC \(p\) with the length of \(N_p\) is inserted in front of the multi-carrier signal to gen-
erate the TDS-MC-CDMA signal frame $s$ with the length of $N_s = N + N_p$, which can be denoted as

$$s = [x^T P^T] = p_{zp}^T + F_{zp}^H \cdot X,$$

(4)

where $p_{zp} = [p^T 0_n]^T$, $F_{zp}^H = [0_n N_p I_n^T]^T \cdot F_N^H$, $F_N^H$ is the $N \times N$ IDFT matrix, $0_{m \times n}$ denotes $m \times n$ matrix of zeros, $I_n$ is the $N \times N$ identity matrix, $(\cdot)^T$ presents matrix transposition, and $(\cdot)^H$ means the Hermitian operation.

At the receiver, the main difference between TDS-MC-CDMA and MC-CDMA systems lies in the removal of ISI caused by TS. Similar to the time-domain PN sequence in the TDS-OFDM system, the PN-MC sequence would destroy the orthogonality of the multi-carrier signal due to ISI, and the effective IPS algorithm in [5] can be directly utilized to remove ISI in the proposed TDS-MC-CDMA system. The difference is that the proposed PN-MC sequence could bring better CE performance, as explained in Sect. 2.1. The following processing including demodulation and despreading is the same as that in the MC-CDMA system. The complexity of the TDS-MC-CDMA receiver is slightly higher than that of the MC-CDMA receiver because of the iterative method for interference cancellation, but the spectrum efficiency is increased without frequency-domain pilots.

The major difference between the TDS-MC-CDMA system and the TDS-OFDM system adopted by Chinese DTTB standard is that, CDMA technology is combined, enabling TDS-OFDM with good multiple access capability. TDS-MC-CDMA can support larger number of users than the TDS-OFDMA system where small number of users is preferred [8]. Besides, the TS is not the PN sequence used in the TDS-OFDM system, but the proposed PN-MC sequence with superior features for both synchronization and CE. Since the PN-NC sequence can be freely designed in the frequency domain, PN-NC with low peak-to-average power ratio (PAPR) is highly preferred.

### 3. Simulation Results

Simulations are carried out to evaluate the performance of the proposed PN-NC sequence and the TDS-MC-CDMA system. Three types of multi-carrier systems without channel coding are assumed: 1) The conventional MC-CDMA system with 10% comb-type pilots insertion and minimum mean square error (MMSE) equalizer [2]; 2) The TDS-OFDM system with PN420 mode adopted by Chinese DTTB standard [5]; 3) The proposed PN-NC training sequence aided TDS-MC-CDMA system. For comparison, the PN-NC in the frequency domain is identical with the time-domain PN sequence used in PN420 mode specified in [6]. The 420-point PN sequence is composed of the 255-point m-sequence and its 165-point cyclic extension. The m-sequence is generated by the linear feedback shift register (LFSR) with generator polynomial of $x^8 + x^7 + x^5 + 1$. The Walsh-Hadamard codes with the length of 16 are utilized for spreading and the number of users is 4 both in the TDS-MC-CDMA and the MC-CDMA systems. The signal bandwidth is 4.096 MHz. The subcarrier spacing is 2 kHz and the number of subcarrier is $N = 2048$. The length of the PN-NC sequence is $N_p = 420$. The modulation scheme is QPSK. The multi-path channel model from State Administration of Radio Film and Television (SARFT) of China, as shown in Table 1 [5], is used. We assume the user-specific channel is Rayleigh fading independently, and use the maximum Doppler spread $f_d = 20$ Hz and $f_d = 100$ Hz with the corresponding receiver velocity of 28 km/h and 140 km/h in the TV UHF band @770 MHz, respectively.

Figure 4 compares the CE performance in terms of mean square error (MSE) and the bit error rate (BER) performance between the traditional TDS-OFDM system and the proposed TDS-MC-CDMA system with spreading factor (SF) of 1 over the static SARFT channel. When the SF equal to 1, the TDS-MC-CDMA system is simplified to be a TDS-OFDM system, disregarding to their difference in the

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<th>Table 1 SARFT channel model.</th>
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<td>Tap</td>
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<td>Delay ($\mu$s)</td>
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Fig. 4 Channel estimation and BER performance comparison between TDS-OFDM and the TDS-MC-CDMA (SF = 1) over the static SARFT channel.
For CE, the SNR improvement of about 3 dB can be achieved by PN-MC sequence compared with PN sequence, since PN-MC sequence has flat frequency response in the frequency domain. Consequently, the TDS-MC-CDMA system outperforms the conventional TDS-OFDM system in terms of BER, but the SNR improvement is not obvious, since the BER performance is mainly limited by the strong frequency-selectivity of the used channel, not the CE performance.

Figure 5 shows the BER performance comparison between TDS-OFDM, MC-CDMA and TDS-MC-CDMA systems over the SARFT Rayleigh fading channel. We can find that the TDS-MC-CDMA system outperforms the TDS-OFDM system mainly because of code spreading, while TDS-OFDM has higher effective transmission data rate due to its single-user operation. TDS-MC-CDMA holds very similar BER performance with MC-CDMA. When \( f_d = 20 \text{ Hz} \), the tiny performance deterioration below the SNR of 10 dB is caused by the interferences between the PN-MC sequence and the multi-carrier signal in the TDS-MC-CDMA system, which could be efficiently eliminated but not totally. The small performance improvement above the SNR of 20 dB is contributed by the elimination of interpolation errors of pilot-aided CE in the MC-CDMA system. The similar conclusion could be applied to the scenario when \( f_d = 100 \text{ Hz} \).

4. Conclusion

The insertion of the proposed PN-MC training sequence makes the novel TDS-MC-CDMA system outperform the traditional MC-CDMA system in spectrum efficiency with quite similar BER performance. The adoption of CDMA enables TDS-OFDM to have the good multiple access capability which could extend the application of TDS-OFDM from broadcasting to other multi-user application scenarios.

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References